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A correction current injection method for power flow analysis of unbalanced multiple-grounded 4-wire distribution networks

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ABSTRACT

Power flow analysis of distribution networks incorporating LV consumer representation needs to be cognizant of an unbalanced load structure and the grounding network between the consumer and network operator (TNC-S earthing). In this paper, the asymmetrical 3-phase (and neutral) power flow problem is solved by a *correction current injection* methodology applied to a system represented by a complex admittance matrix. The correction current injection technique is adopted to adjust the power exchange of shunt elements, whose nominal admittances are included in the system admittance matrix, through suitable fringing currents in the iteration process. This methodology offers an improved and more robust alternative for asymmetrical network scenarios under unbalanced power flow conditions when compared to the standard power flow methodologies, such as the *Newton–Raphson* or the *forward–backward sweep* approaches. These well-known methods may encounter convergence issues as a consequence of the specific consumer/network earthing arrangements especially when they need to be defined throughout the network. The algorithm presented here has been applied to a 4-wire representation of a suburban distribution network within Dublin city, Ireland, which incorporates consumer connections at single-phase (230 V N). The analysis presented uses the *correction-current injection* power flow algorithm in conjunction with the network model to consider the impact of distributed wind and solar (PV) generation systems (*DwG* and *DpvG* respectively), for a range of load profiles.

1. Introduction

More than half the World's population lives in urban areas, occupying less than 3% of the Earth's ice-free land area. Cities are responsible for between 71% and 76% of CO_2 emissions from global final energy use [1], much of it derived from fossil-fuel based electricity generation. Moving toward a more sustainable economy, urban areas need to develop smart energy networks that can both generate and deliver *renewable* electricity in a predictable and consistent manner. Significant momentum is being achieved in economic "greening" and in 2011 alone, renewable energy sources accounted for 44% of new generation added worldwide [2]. While the majority of this new capacity comes from larger plants (such as wind farms), the influence of the *residential sector* should not be underestimated and in countries such as the UK, significant efforts are being made to capture this market [3,4]. The residential portion of total energy use accounts for 32.79% [5] and 30.9% [6] in the US and Euro zone, respectively. The connection of small and micro-generation at consumer level could contribute positively toward national renewable energy targets; particularly in a smart grid context. This kind of evolution requires a more integrated, distributed and bi-directional energy supply chain, which is representing a tough challenge for distribution network operators. These networks were originally designed for a vertically integrated power system with several large power plants and a mainly passive grid. The presence of generation units in distribution networks leads to the need for a detailed modeling of those systems with a particular focus on the LV grid which is generally an asymmetrical network with unbalanced loading conditions on the three phases. The power flow calculation is used to compute the steady state operating condition of a power system and its solution should be fast, require low storage requirements and be reliable and versatile through an inherent simplicity [7,8]. The algorithms generally adopted are *Gauss–Seidel* or *Newton–Raphson* (and its decoupled versions [9]) which are sufficiently robust and fast even for large networks but do not allow a very easy extension to a multi-phase system. This aspect can be neglected when considering transmission systems (considering the single-phase equivalent circuit) but it

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could assume an important role when unbalanced load and generation scenarios are involved, as in distribution networks. In a recent review of Power Flow studies, Balamurugan and Srinivasan [10] describe how three-phase power flow analysis can be considered in terms of two different reference frames, namely the *phase frame* and the *sequence frame*. The phase frame, incorporates methods such as forward/backward sweep, (Kirchoff) compensation, implicit z_{Bus} Gauss method and modified Newton/Newton-like methods. They all consider unbalanced quantities directly. On the other hand, the sequence frame employs decoupled positive, negative and zero sequence networks to represent the unbalanced three-phase system and to solve the unbalanced three-phase power flow. The multi-conductor *correction-current injection* power flow methodology presented in this paper uses a phase frame reference. All the network elements are represented through suitable admittances in order to result into a system's admittance matrix including all the network's phases. A similar approach seems to be used by the OpenDSS software released by EPRI [11,12], which also employs a phase frame of reference for the solution of the power flow problem in generic *n*-phase networks.

This paper provides a detailed description of the asymmetrical *n*-phase power flow solution presented in [10], which is based on a complex admittance matrix methodology [13] to consider a representative urban distribution network [8,14]. The system admittance matrix is obtained through the definition of self and mutual couplings among the phases in order to allow the representation of any number of phase and earth conductors (e.g., neutral conductor, earth wires and shields). In the iterative power flow calculation loop a "Fringing" Correction Current (FCC) methodology is adopted to include the required voltage dependency of shunt elements through a suitable correction current injection in parallel to load/generation rated admittance(s). The power flow algorithm (FCC) facilitates balanced and unbalanced distribution system solutions, which can be radial or meshed. Furthermore, the algorithm is sufficiently flexible to allow considering *n*-phase line configurations. In this paper, it has been applied to a 3-phase/4-wires LV real network considering also the systematic earthing along the lines (TN-CS). The aim of the paper is to provide a thorough description of the *correction-current injection* power flow methodology, giving a detailed description of how to model the elements and to demonstrate its applicability on a section of Irish active LV distribution network under unbalanced operating conditions. A comparison of the results obtained from the proposed methodology and the software OpenDSS and PowerFactory is reported to validate the results.

2. Asymmetrical power flow method

In this section, a description of the algorithm adopted for the asymmetrical power flow analysis is provided. This *correction-current injection* algorithm evolved from the complex admittance matrix power flow methodology described in [13] by including a multi-conductor network structure in order to consider any number of phase and earth conductors. The main feature of this method is the inherent flexibility in how multi-conductor network models and their associated effects are considered. Mutual coupling influences between phases are computed through a method that was originally developed for calculating electromagnetic coupling of complex conductor geometries [15]. The use of such a multi-conductor approach facilitates accounting for any kind of interaction between phases meaning that any network shunt element connections can be considered in terms of the system's phase and reference potentials and with respect to specific grounding (earthing) options. This feature intrinsically allows any generic network with asymmetrical structure and operating under unbalanced conditions to be considered.

Fig. 1 shows a typical distribution system, incorporating network structure, load, generation and grounding elements. The branch element admittance matrix is composed through an incidence matrix approach [16] computing the mutual admittances between the system's buses, which are represented as *n*-phase ports ("nodes"). The network shunt elements and grounding admittances are connected to these nodes, providing a linkage between the phase potentials and the system ground.

2.1. Branch elements

Branch elements are included in the network admittance matrix by considering a n-phase π-model. Each branch admittance matrix comprised longitudinal impedance $\mathbf{Z}$ and transversal admittance $\mathbf{Y_t}$ matrices as described in Eq. (1) and illustrated in Fig. 2:

$$\mathbf{Y_{Branch}} = \begin{bmatrix} \mathbf{Z}^{-1} + \dfrac{\mathbf{Y_t}}{2} & -\mathbf{Z}^{-1} \\ -\mathbf{Z}^{-1} & \mathbf{Z}^{-1} + \dfrac{\mathbf{Y_t}}{2} \end{bmatrix} \tag{1}$$

The so-called $\mathbf{Y_{Branch}}$ represents the relationship between currents (positive if entering) and voltages (with respect to a common zero-voltage reference) of the 2*n* ports of the branch element. The construction of the $\mathbf{Z}$ and $\mathbf{Y_t}$ sub-matrices within the π-model is obtained using the classical Carson-Clem formulation for a *n*-phase branch as described in [15]. An approximation of the correction terms for the real and imaginary components of the external part of the self and mutual impedance with earth return, is also provided in [15]. It is important to note that in practical cases these correction terms could be the dominant impedance in the 4-wire model, especially when considering unbalanced operation. The longitudinal impedance matrix $\mathbf{Z}$ contains the self and mutual impedances for each phase. Given two circuits *i* and *j* those terms are calculated as in Eqs. (2) and (3):

$$\mathbf{Z}_{ii} = R_i + R_e + j\omega \times 2 \times 10^{-4} \ln\left(\frac{D_e}{r_i}\right) \left[\frac{\Omega}{\text{km}}\right] \tag{2}$$

$$\mathbf{Z}_{ij} = R_e + j\omega \times 2 \times 10^{-4} \ln\left(\frac{D_e}{d_{ij}}\right) \left[\frac{\Omega}{\text{km}}\right] \tag{3}$$

where,

R_i: DC resistance [Ω/km];
r_i: phase conductor radius [m];
d_{ij}: mutual distance between conductors *i* and *j* [m].

In Eqs. (2) and (3), the hypothesis of soil finite conductivity is duly considered by an earth return path with depth D_e and resistance R_e [15], as defined in Eqs. (4) and (5) below:

$$R_e = \pi^2 f 10^{-4} \left[\frac{\Omega}{\text{km}}\right] \tag{4}$$

$$D_e = 659\sqrt{\frac{\rho}{f}} \quad [\text{m}] \tag{5}$$

where,

f: system frequency [Hz];
ρ: soil conductivity [Ωm] (typically 100 Ωm).

The transversal admittance matrix $\mathbf{Y_t}$ represents the capacitive self and mutual susceptances, as evaluated through the Maxwell's potential coefficients. For the power flow problem in LV networks however, these terms have only a marginal effect.